CONTROLLED TURBULENCE AS A DESIGN CRITERION FOR ELECTRIC DISCHARGE CONVECTION LASERS

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THESIS

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FOR ELECTRIC DISCHARGE CONVECTION LASERS

by

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Controlled Turbulence as a Design Criterion
for Electric Discharge Convection Lasers

by

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ABSTRACT

This thesis is primarily concerned with the application of controlled turbulence to electric discharge convection lasers (EDCLs). A preliminary design of a closed-cycle, EDCL system has been accomplished. Experimental investigations into the mechanism of turbulent flow and its stabilization of gaseous, electric discharges were made. Spectral distribution, velocity profile, and power consumption data taken in a discharge region are presented. Turbulence was generated by various screens or combination of screens in an attempt to further understand the phenomena involved.

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The author gratefully wishes to acknowledge Associate Professor Oscar Biblarz for his guidance and encouragement during the course of these investigations and the technical staff of the Department of Aeronautics under R. Besel and T. Dunton, particularly C. Gordon and R. Ramaker for their able assistance in the fabrication and assembly of the equipment used in this study, and to acknowledge my wife and family for their patience and encouragement.

I. INTRODUCTION

Electric-discharge convection lasers (EDCLs) offer much promise for commercial and special-use military applications of continuous wave (CW), high-power laser technology. These laser systems utilize gases that are relatively common and safe; namely, carbon dioxide, nitrogen, and helium.

At present more is known about the mechanisms of the CO_2 laser than any other high-power laser. In 1961 Polanyi Ref. 2 first suggested using rotation-vibration transitions for laser action. As early as 1964 Legay and Sommaire Ref. 2 suggested the excitation of CO_2 by active nitrogen. Intensive scientific probing into the physics of the CO_2-N_2 laser has led to a thorough understanding of this system.

In the laser process, the population inversion is achieved by exciting nitrogen to its first vibrational level via collisions with electrons in the discharge. A nearly resonant vibration-to-vibration energy transfer then takes place between the excited N_2 and the CO_2 upper lasing level. The CO_2 laser has one of the highest known quantum efficiencies, i.e., ideal energy conversion efficiency, being approximately 40 per cent.

Nitrogen excitation, or pumping, and carbon-dioxide lasing action can be achieved by chemical, gasdynamic, or electrical means. Chemical means are the most efficient, but are the least developed. Gasdynamic lasers are the least efficient, but are the most developed laser system. In between lies the electrical laser with a good potential in efficiency and power levels. Multi-kilowatt power levels have been obtained with slow-flow electric-discharge CO_2 lasers Ref. 14 , but better results are obtained by fast-flow systems. The latter systems more readily avoid chemical poisoning and deteriorative temperature increases in the discharge region.

Continuous output power levels on the order of 27 kW have been obtained from a closed-cycle EDCL that employs fast-flow rates Ref. 3 .

The majority of EDCLs that have been built operate well below atmospheric pressure, on the order of 100 torr or less. This has been necessary because of the difficulties encountered in getting a good discharge to work at higher pressures. It has been shown that the introduction of controlled turbulence into the discharge region greatly enhances discharge performance (Refs. 1, 3, 4, 5, 6, 8, and 13). The term discharge performance entails how homogeneous the charge density is between electrodes, how the current fluctuates, and how much power can be put into the discharge region before arcing or breakdown destroys the glow discharge. Although turbulence somewhat degrades the beam quality of a laser, the benefits of increased power output may override this consideration. It is believed that once the optimum type of turbulence is found and its generation controlled, suitable optics can be developed that will compensate for the degraded beam quality.

This thesis is part of a project in the Department of Aeronautics at the Naval Postgraduate School that has as an ultimate objective the feasibility demonstration of a high-power, CW electric-discharge convection-laser operation in a closed-cycle system at near atmospheric pressures. It is felt that the bridge between laser performance at reatively low pressures and laser performance at near atmospheric pressures lies in conditioning the flow with turbulence. It is also felt that this flow conditioning is as important a design criterion as is the cavity engineering or optics design that affects laser performance and efficiency. Higher power outputs need a higher operating pressure and more flow velocity.

LT Nelson began this project at NPS by studying electric discharges in atmospheric air Ref. 13 . He confirmed that a certain kind of turbulent flow does stabilize an electric-discharge and allows the discharge to accept

more power. His data reflected as much as a 250-fold increase in power over the no-flow case. This thesis expands LT Nelson's work and ties it to the preliminary design of a closed-cycle CO_2 laser system.

It is reported that turbulent flow compensates for velocity defects introduced by electrode elements Ref. 6 . The eddies of this turbulence must also be of the proper size and intensity to mix and spread out the charge concentration that builds up at the electrode. This charge build-up is likely what causes arcing or breakdown of the discharge. All of this seems to indicate the importance of a very homogeneous, turulent flow field in the discharge region.

The majority of LT Nelson's turbulence data were taken by placing a hot-wire probe directly in the wake of the center cathode element. The above discussion suggests that further research is needed to investigate the homogeneity of the turbulence in the discharge region. Spectral analysis is also chosen here to study the turbulent flow. This type of analysis uses the distribution of root mean square turbulent energy as a function of frequency in order to characterize the flow. A constant temperature hot-wire anemometer connected to a real-time analyzer provides the fast reponse time that is required to get reliable spectral distribution data. Besides additional turbulence data taken, the dimensions of Nelson's equipment were changed in order to expand the volume of the discharge region and in order to integrate the test section into a closed-cycle system.

II. CLOSED-CYCLE SYSTEM DESIGN

High-power, CW application of EDCLs, such as welding and cutting, require long operating times. In military and commercial applications of high-power lasers, compactness of the system is high on the list of priorities. These facts indicate that EDCL operation in a closed-cycle system, i.e., a system that continuously recirculates and reuses the laser gases, is very much desired. In a closed-cycle EDCL one can control constituent gases, velocities, temperature, and to some extent, pressures. Also, precious gases such as helium are not wasted.

Because the project at NPS is currently unsponsored, the components of the present closed-cycle system design are limited to those at hand or to those that can be found through government-surplus supplies. Figure 1 depicts the system that is envisioned for this project without such severe budget constraints. The system is to be slanted in order for the test section to be at table height and heavy equipment such as a compressor to be on the floor. This layout is desirable to facilitate incorporation of the laser cavity and test equipment.

The following components comprise those that are presently available. The main piping selected is Alcoa seamless 6067-T6 aluminum pipe. This piping has an outside diameter of 8 inches and a thickness of 0.065 inch. The design criterion of controlling constituent gases necessitates the ability to purge the system of contaminant gas species, i.e., air, prior to gas filling. A Welch 1397B, Duo-Seal Vacuum Pump with a rated capacity of 10^{-2} mm Hg is available for this purpose. McLeary and Gibbs (Ref. 12) have found that a gas mixture with CO_2:N_2:He ratios (by volume) of 1:19:430 produces near-optimum excitation of the upper lasing level when operating

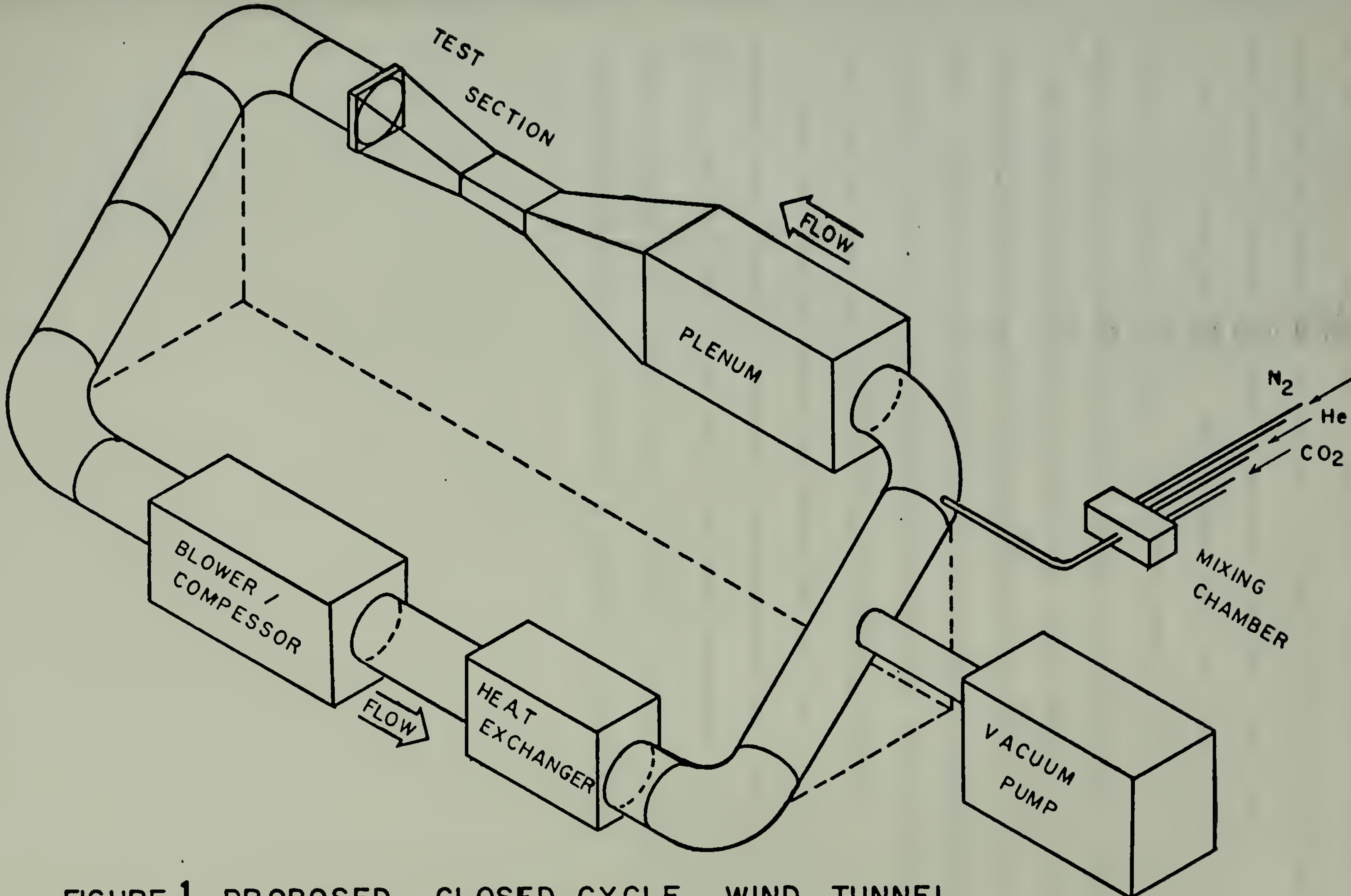


FIGURE 1. PROPOSED CLOSED-CYCLE WIND TUNNEL

in the CW mode at near atmospheric pressures. Ratios of this type can be controlled by flowing bottled gas into a mixing chamber and monitoring the inlet pressures before introducing the gases into the closed loop.

The heat exchanger design has been postponed until the required cooling rates are better known. A water-cooler heat exchanger seems to be the most practical since most laboratories have available an ample water supply system.

The plenum, nozzle, and test section have been designed and constructed to specifications that permit easy incorporation into the closed-cycle system. These components were used for the experimental investigations of this thesis and will be described in the next section. The rest of the closed loop has been designed but not manufactured at this time.

A pump that has the desired performance has not been located through the existing supply channels. Appendix A details the desired characteristics and compares them with a commercially available compressor that can be purchased for about $4000. Flow rates or velocities for this compressor can be controlled by varying the speed of a suitable drive mechanism.

III. EXPERIMENTAL APPARATUS

In order to investigate further the effects of turbulence on an EDCL channel and in order to scale up LT Nelson's test section for incorporation into a closed-cycle system, a new test apparatus was designed. Since this investigation was directed only at the study of discharge characteristics, atmospheric air was used as the working medium. (The discharge characteristics of air are comparable to EDCL gas mixtures.) This air supply was delivered by a Carrier three-stage centrifugal compressor which is capable of delivering 4,000 ft^3/min at a maximum pressure ratio of two.

A picture of the laboratory and associated test equipment can be seen in Figure 2. Plexiglass was used to fabricate the plenum, nozzle, and test section because of its high dielectric properties, ease of construction, and its transparency. Originally, 0.25-inch plexiglass was used for the plenum, but was found to be too weak to withstand some of the high pressures encountered. These pressures resulted from flow blockage associated with several of the turbulence generating screens that were tested. Subsequently, 0.75-inch plexiglass was used. A 10-to-1 area ratio was designed to give the anticipated flow velocities. A test sectional area of 2 x 4 inch was decided upon in order to be compatible with existing equipment. These considerations dictated a 9 x 9 inch plenum cross section. A nozzle length of 1.5 ft was found satisfactory for smooth flow transition with minimal pressure losses. The thickness of the nozzle remained 0.25 inch, but the seams were re-inforced with additional plexiglass and the circumference was banded with metal strips. Just upstream of the nozzle an aluminum honeycomb was placed in the plenum in order to straighten the flow and to dampen upstream turbulence.

A pin/airfoil electrode design was chosen to produce the corona discharge because it offers a much cleaner aerodynamic design over an arrangement of multiple discharge tubes. The airfoils were machined from 0.5 x 0.125-inch brass strips and the pins were made from 0.0625-inch steel wire. It might be interesting to note here that these materials did not appreciably change the characteristics of the discharge from the results that Nelson Ref. 13 achieved using aluminum electrodes. Details of the design can be seen in Figure 3. The spacing between electrodes was originally 1.625 inches, but had to be shortened to 1.5 inches because of power supply limitations. The walls of the test section contained 0.0625-inch slots placed 0.25 inch apart in order to minimize the voltage leaks that are associated with a film of moisture that tends to collect on the walls of the channel. Figure 4 shows the assembled test section.

Because in part of this work we attempted to correlate the eddy size and intensity of turbulence to electric-discharge performance, screens of various grids were chosen to generate the turbulence. Screens that were not rigid enough to stand alone were mounted into plexiglass holders which became part of the test section. The screens were positioned 0.5 inch upstream of the pins. Along with Figure 5, Table I describes the screens that were tested.

Flow velocity was measured by a pitot-static probe connected to a Meriam Instrument Company micro-manometer. Relative humidity and temperature of the air were measured with a General Eastern 400 relative humidity and temperature indicator. Test section velocity profiles were recorded by using the linearized output of a Thermo Systems Inc. hot-wire anemometer consisting of a model 1051-2 monitor and power supply, and a model 1054A-30 anemometer module. The hot-wire probes and filament mounting were constructed locally. The filaments were 0.00015 inch diameter tungsten. The wire was

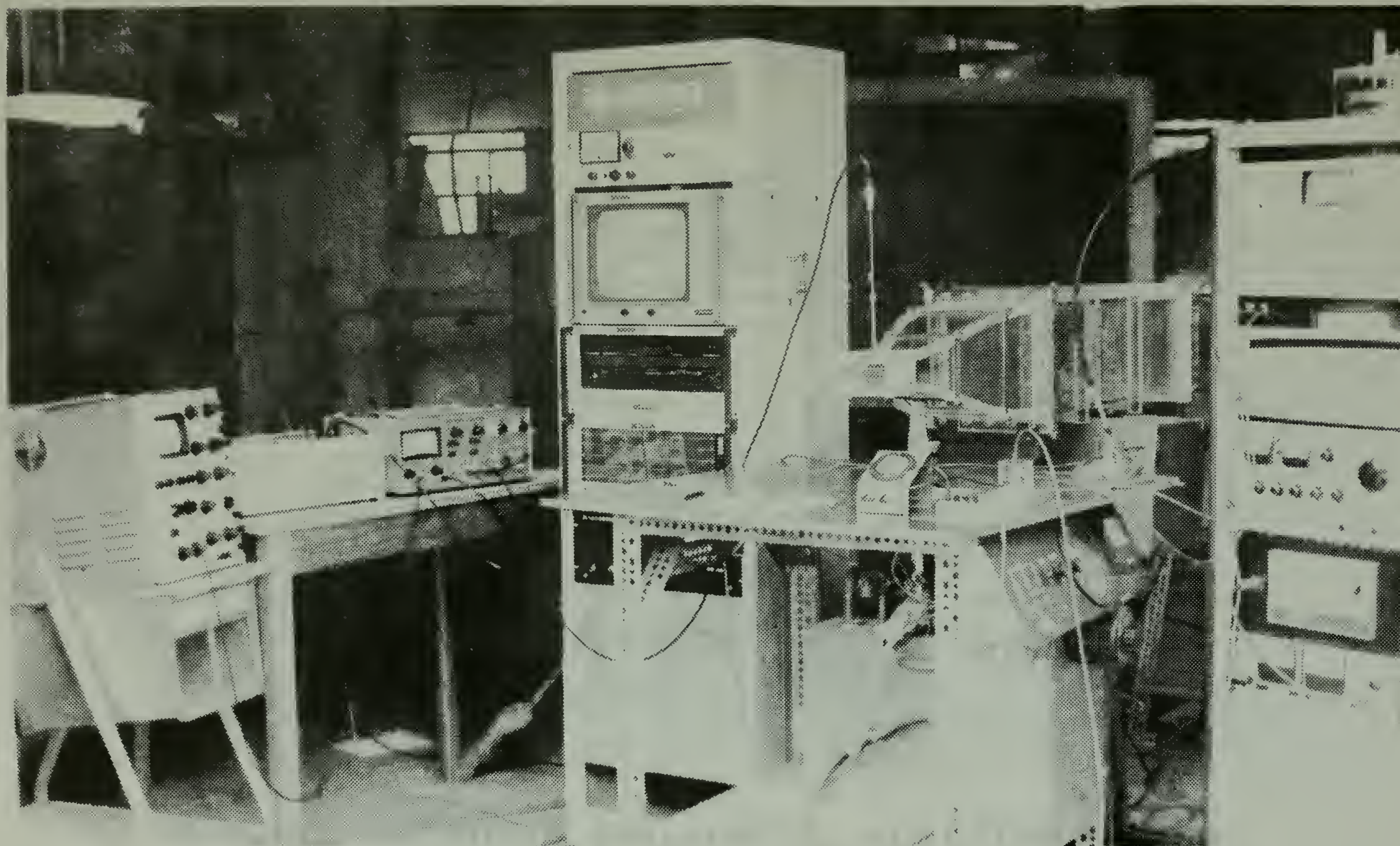


FIGURE 2. THE LABORATORY

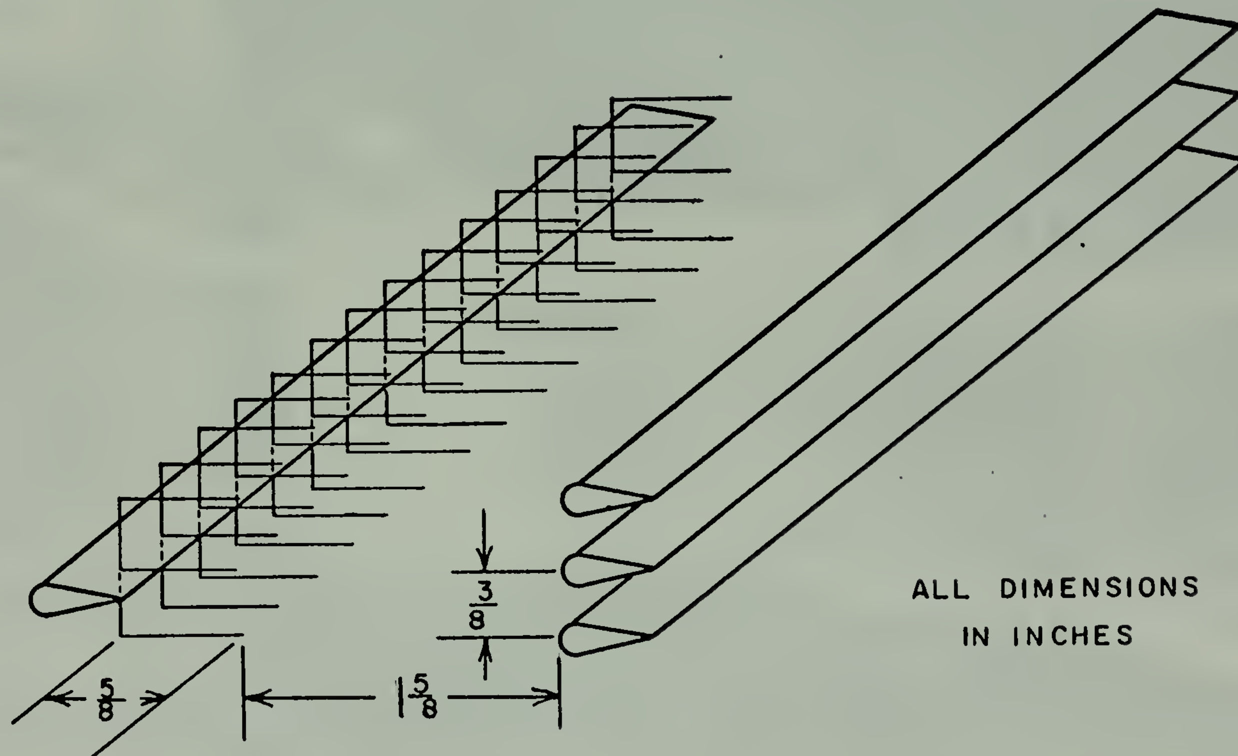


FIGURE 3. DETAIL OF PIN/AIRFOIL ELECTODE DESIGN

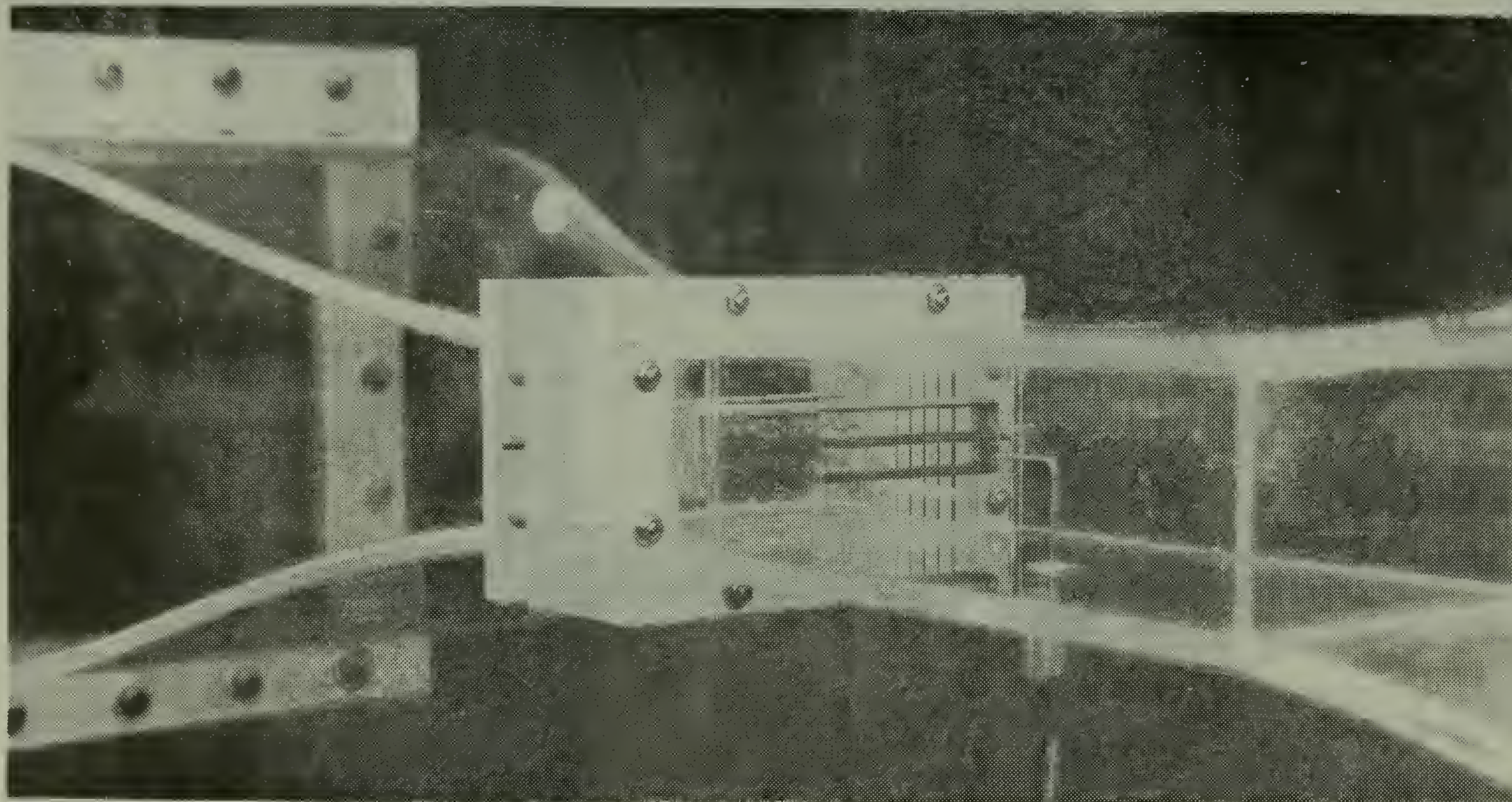


FIGURE 4. ASSEMBLED TEST SECTION

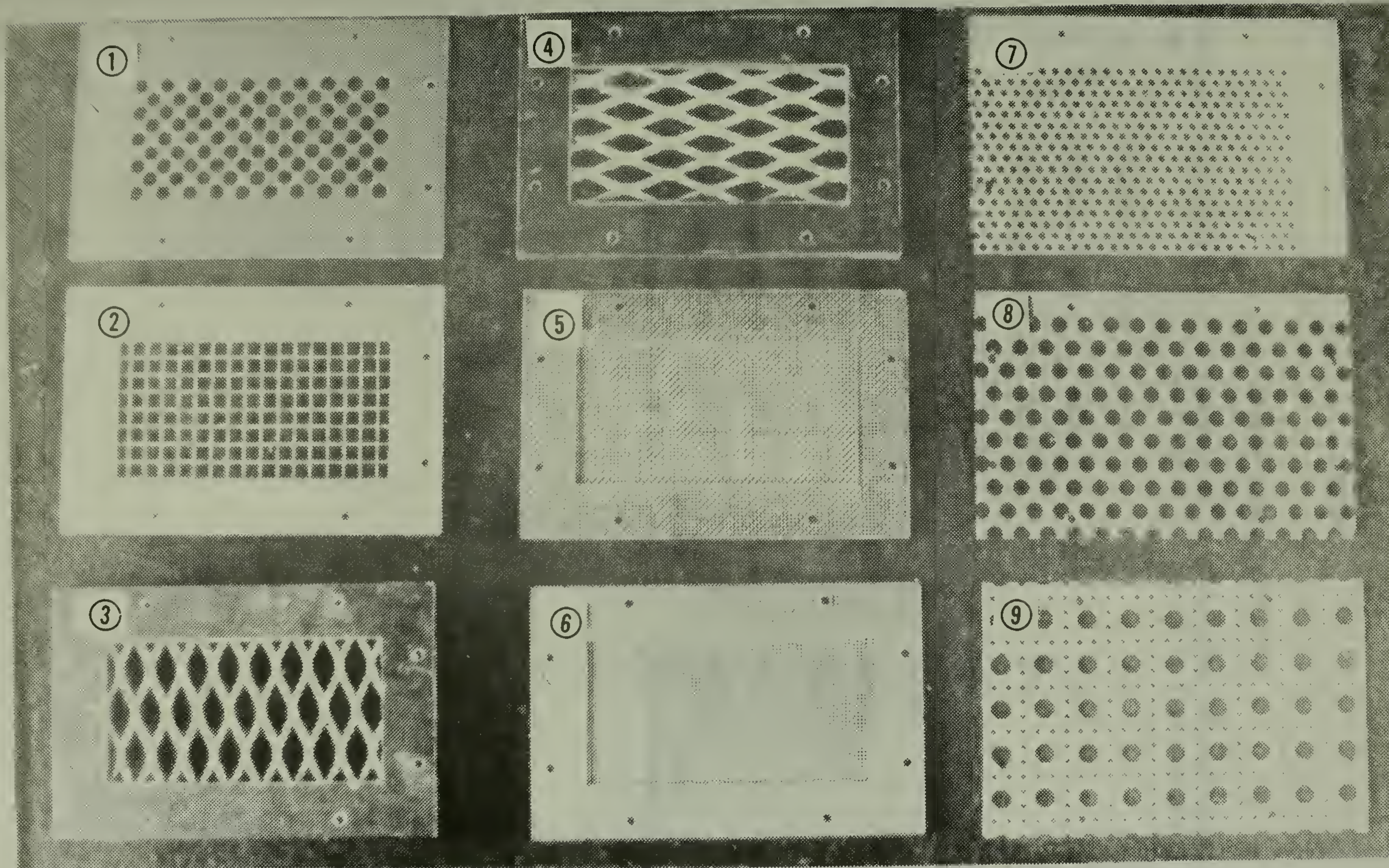


FIGURE 5. SCREENS USED TO GENERATE TURBULENT FLOW

TABLE I

SCREEN SPECIFICATIONS

Screen No.	Material	Diameter of Wire (in.)	Distance Between wires or Hole Diameter (in.)	% Blockage
1	Phenolic plate	N/A	0.25	47
2	Aluminum wire	0.03	0.22	1.2
3	Galvanized wire	0.105	N/A	25
4	Galvanized wire	0.105	N/A	25
5	Brass wire	0.014	0.064	6.7
6	Nylon strands	0.008	0.04	2.0
7	Sheet aluminum	N/A	0.125	61
8	Sheet aluminum	N/A	0.25	61
9	Sheet aluminum	0.101	0.125	78
9a	Sheet aluminum	0.136 holes	0.125 length of hexagon side	69

copper plated at the solder joint points so as to insure electrical integrity when fastened to the probe.

Turbulence measurements were made with the hot-wire system output connected to a General Radio Company, Type 1921, real-time analyzer. This analyzer consists of a model 1925, 30 channel multifilter and a model 1926 multichannel RMS detector. The detector processes signals from the multifilter digitally with a variable integration time. The processed signal is stored until displayed on Nixie tubes. The display rate was controllable, thus enabling the experimenter to record data by hand and/or by use of an X-Y recorder. Both data taking methods were used, with the former being more satisfactory. Some difficulty was encountered with synchronizing a Honeywell model 320 X-Y Recorder with the analyzer output. The output of the analyzer was also connected to a Hewlett-Packard model 1300 X-Y display to provide a rapid visual trace of relative spectral intensities. A Tektronix oscilloscope was also connected to the hot-wire anemometer for maximizing the frequency response sensitivity and to provide a continuous monitor of the hot-wire operation. A schematic of the instrumentation is shown in Figure 6.

The electric-discharge power was furnished by a Sorensen High-Voltage, D.C. power supply. This unit has an output of up to 30 kilovolts (kV) and 20 milliamperes (ma) with a 2% ripple. The high voltage was measured with a Sensitive Research electrostatic voltmeter having an internal impedence of 5×10^5 ohms and a maximum range of 40 kV. Current measurements were made with several Simpson microammeters and milliammeters. All leads were made of high-voltage wires. All high-voltage connections were made through highly polished, brass spheres. The laboratory has its own grounding system and proper grounding of all equipment was diligently observed. The electrical connections are shown in Figures 7 and 8.

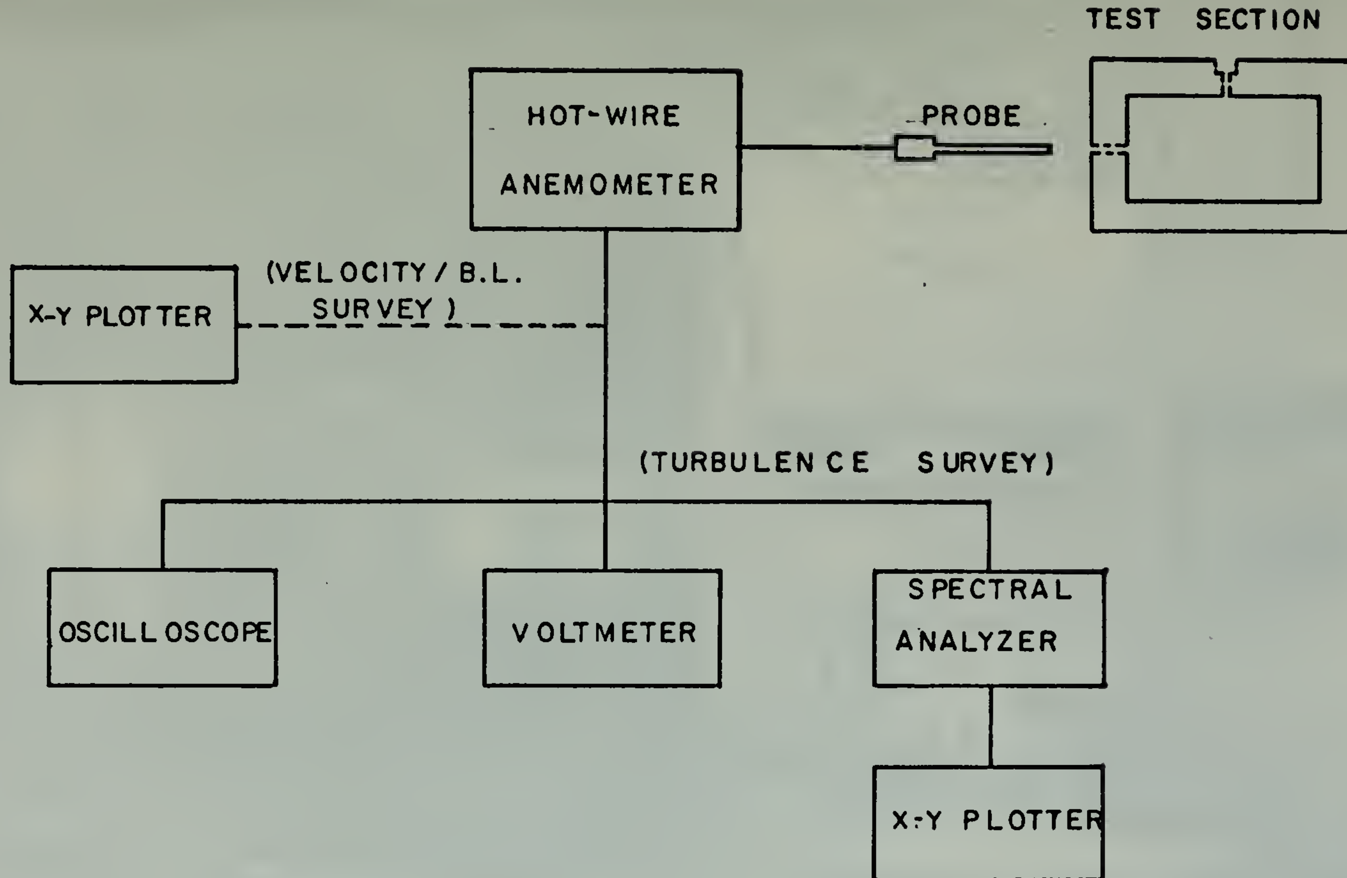


FIGURE 6. BOX DIAGRAM OF TEST SECTION SURVEYS

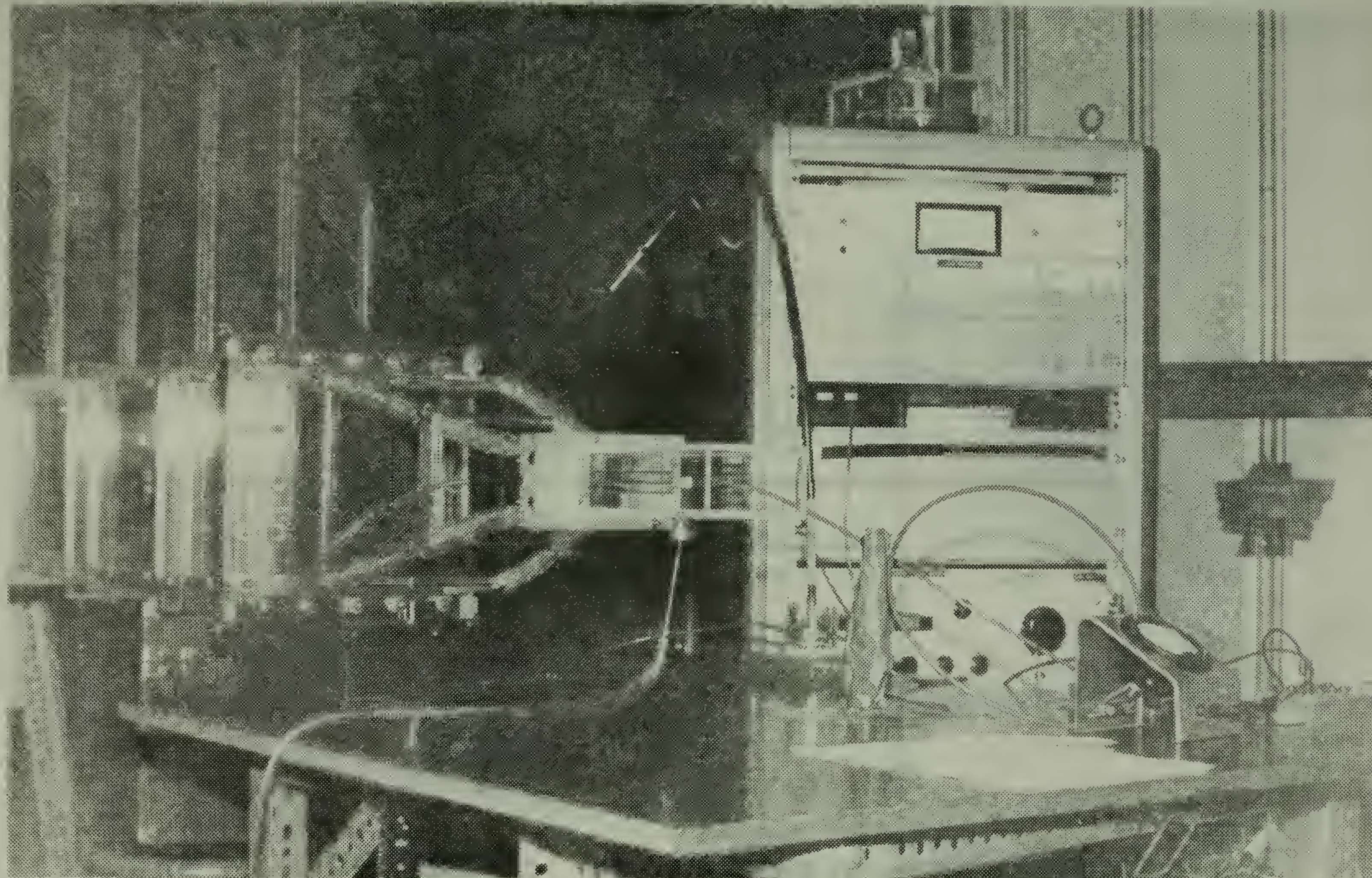


FIGURE 7. ELECTRIC-DISCHARGE DATA COLLECTION SET-UP

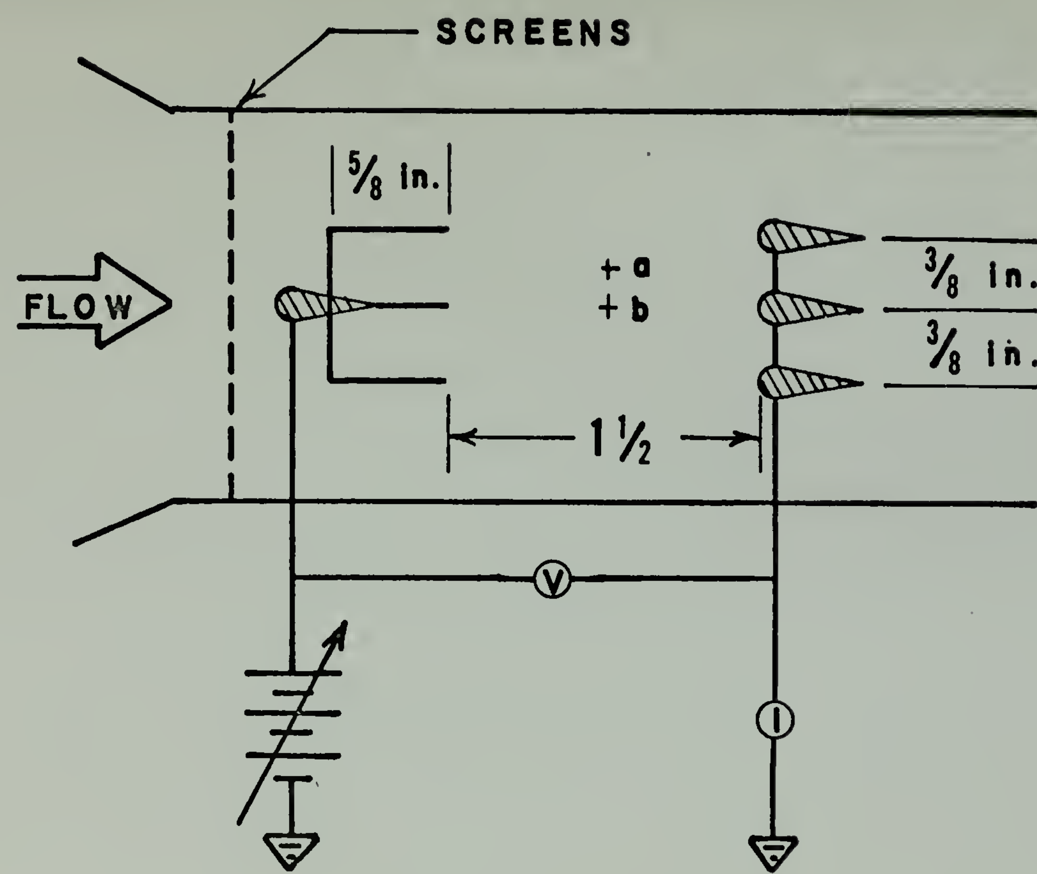


FIGURE 8. SCHEMATIC OF DISCHARGE DATA COLLECTION SYSTEM.

Because several of the screens tested imposed greater than 50% flow blockage, the pressure loss across them became significant. A separate test section having the same cross-sectional dimensions as the lasing channel was constructed so that pressure drop measurements could be taken. Static pressure losses across the screens were measured with a mercury, U-tube manometer.

IV. EXPERIMENTAL PROCEDURE

The procedure was broken into two stages, the first one being a preliminary design of the entire closed-loop EDCL system and the second one fabrication and testing of the test section. The testing included obtaining data on velocity, turbulence, pressure, and electric-discharge characteristics.

The design has been described in the preceding sections. Full-scale engineering drawings of the plenum, nozzle, and test section components were made and submitted to the shop technicians for construction. As work progressed, necessary modifications were made.

Hot-wire velocity and boundary layer measurements were taken for the no-screen case with both spanwise and vertical traverses of the test section. The linear output of the anemometer was used. The hot-wire was set by first adjusting the feedback resistance with a built-in variable potentiometer. Since a hot-wire was used instead of hot-film sensors, the REF SET control was then adjusted to read 15 volts. The linear zero was then set in. After the desired flow velocity was achieved, a preliminary traverse of the test section was made in order to determine the location of the maximum velocity. (In all cases this was in the free stream, away from the influence of the pin wake.) This maximum flow point became the reference velocity and the linear span of the anemometer module was set on the 0-300 scale. The reading of 300 represented the maximum flow.

For the turbulence measurements the hot-wire was set up for maximum frequency response by following the instructions of the Thermo-Systems Inc. handbook. These may be summarized as follows: initially, the hot-wire was set up the same as for the velocity traversing; then, with the probe exposed to the maximum flow, the STABILITY control was set full clockwise

and turned back until the output was stable, with the TRIM control set full counter-clockwise; now the TRIM control was turned clockwise until an oscillation developed in the output, and then the TRIM was turned back slightly past the position required to stabilize the output; built-in signal generators were temporarily switched in to aid in this procedure.

Taking the data by traversing from the side was considered unsatisfactory because the probe would remain in the wake of the center row of pins. Spectral data were therefore taken by traversing from the top of the test section, and that data were recorded for the positions labeled a and b in Figure 8.

Calibration checks were made on the real-time analyzer by introducing a known 1 kHz signal. Equipment performance was found to be well within factory specifications.

The discharge work was to be the last of the series of experiments conducted. Great care was exercised to avoid corona voltage leaks. This was accomplished by thoroughly cleaning the power supply and test section, using high-voltage leads, and isolating the high voltage terminals. Cessation of the corona discharge in the test section was considered to occur when an arc formed between electrodes with subsequent automatic power supply shut-off.

V. DISCUSSION OF RESULTS

For the investigations of this thesis, a speed of 200 ft/sec was considered a representative flow rate to provide data on design parameters. Figure 9 shows the channel velocity distributions resulting from hot-wire probes. These data represent the no-screen case and show a fairly homogeneous velocity profile for the horizontal, spanwise traverse. The wake of the upstream airfoil and accompanying center row of pins create an even wake disturbance. The vertical traverse markedly shows the influence of the airfoil/center-pin arrangement on the wake as compared with the effects of the top and bottom pins.

Spectral measurements were made of turbulence in the test section as generated by various screen configurations mounted upstream of the pins. These investigations were aimed at finding a screen or combination of screens that would produce an intense, homogeneous spectral distribution in the discharge region. Using Reference 13 as a guide, attention was focused on the 1 kHz to 10 kHz range of frequencies.

Screens 2,3,4,5,6,7, and 8 and combinations 6&8, 6&4, 6&3, and 6&2 gave spectral distributions almost identical to the no screen case. Nelson's screen combination, i.e., 1 & 6, produced the same distribution behind the center pin for the present test section dimensions as it did for the previous one Ref. 13 . Screen 9 produced what appeared to be the most promising results. Looking at Figure 10 one can see why this was indicated. Screen 9 gave the most homogeneous distribution, i.e., the same distribution at data points a and b, and the most intensity of all the screens tested. Because Nelson's data seem to indicate that there is some interesting phenomenon associated with combining screen 6 with screen 1, data were taken for

fig. (a)

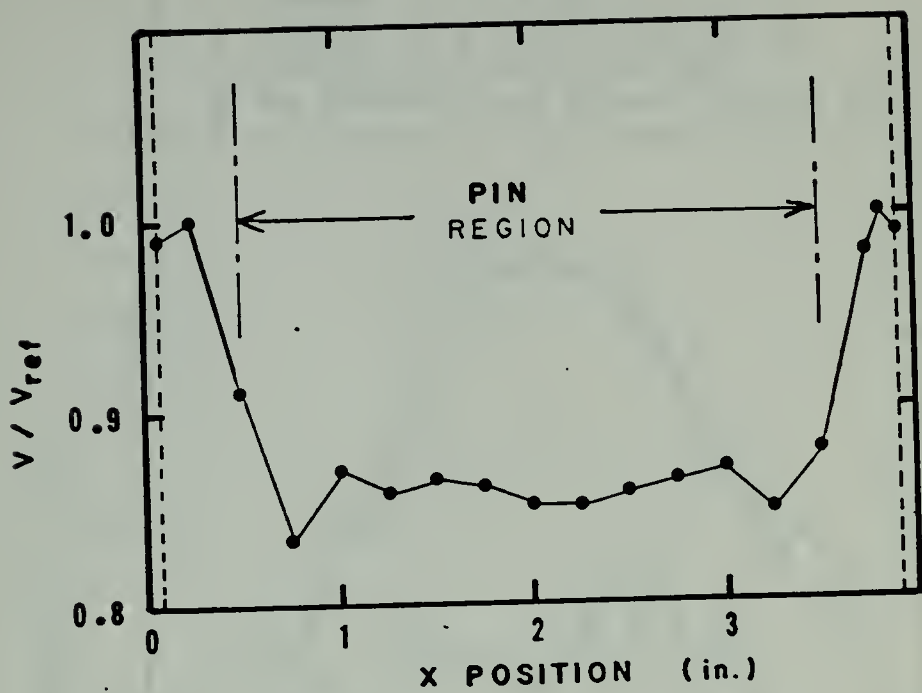


FIGURE 9. VELOCITY PROFILES (a) HORIZONTAL (b) VERTICAL. DASHED LINE INDICATES BOUNDARY LAYER. V_{ref} = 200 FT / SEC

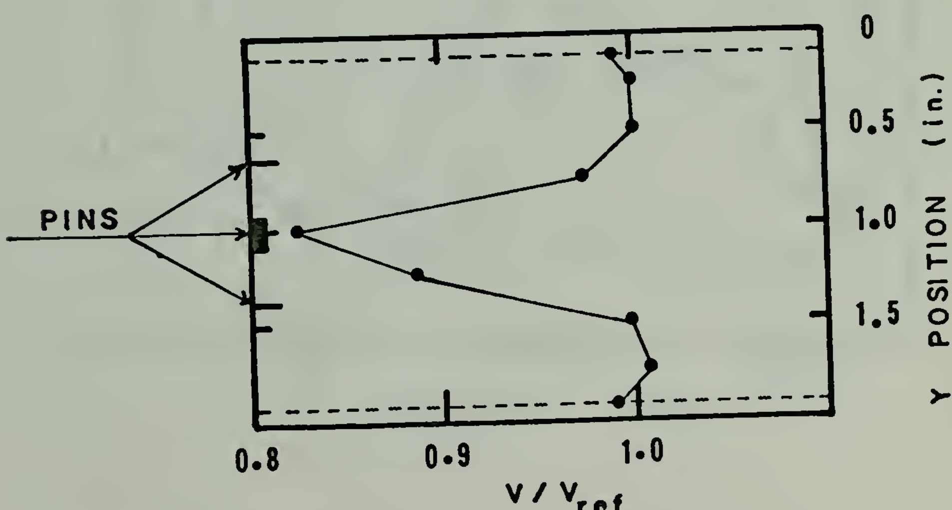


fig. (b)

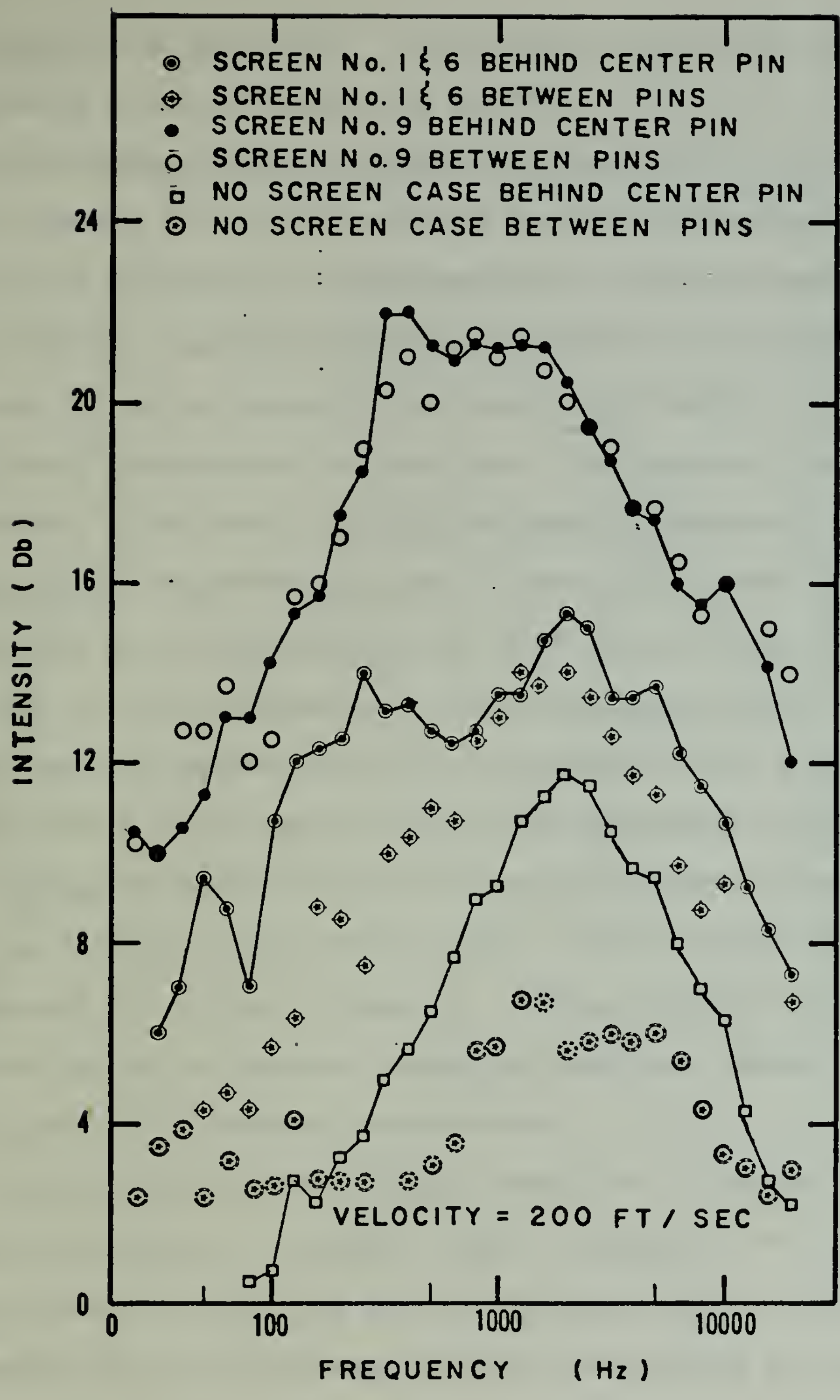


FIGURE 10. COMPARISON OF SPECTRAL DISTRIBUTIONS

the combination of screen 6&9. This, however, produced the same intensity distribution as that of screen 9 by itself.

For all screens tested a frequency spike appeared at 12.5 kHz. At first this was thought to be a malfunction of the General Radio real-time analyzer. To determine the veracity of this assumption, a Spectral Dynamics Corporation, model 330, real-time analyzer was borrowed and comparisons were made. The spike was in fact present. More significant, however, was the essentially exact duplication of previous data. This increased the confidence and credence of this work. The 12.5 kHz spike is considered to be from an outside source. Since the laboratory is physically located almost on the same grounds as the local airport, the spike is most likely coming from a spillover of a strong marker-beacon signal originating there. This one channel spike was omitted from the data presented in this thesis.

The results of the spectral distribution experiments indicate that the flow blockage and associated pressure loss may be important factors in the shape and intensity of the frequency data. Static pressure losses were recorded and are plotted in Figure 11. The top data point for screen 9 is estimated because the original plenum and nozzle were unable to withstand such a pressure drop without reinforcements.

Before proceeding to the discharge work a set of data was taken to visualize the manner of turbulence decay. Textbooks on the theories of turbulence all indicate that the decay of turbulence occurs in stages, i.e., the smaller eddy, high-frequency turbulence decays while the larger eddies cascade in time. This tendency was verified and can be seen in Figure 12. By varying the velocity and taking data at the same point in the flow stream, one can visiualize the same "chunk" of air at different distances from the turbulence generating screens. The slower velocity represents the longest downstream distance.

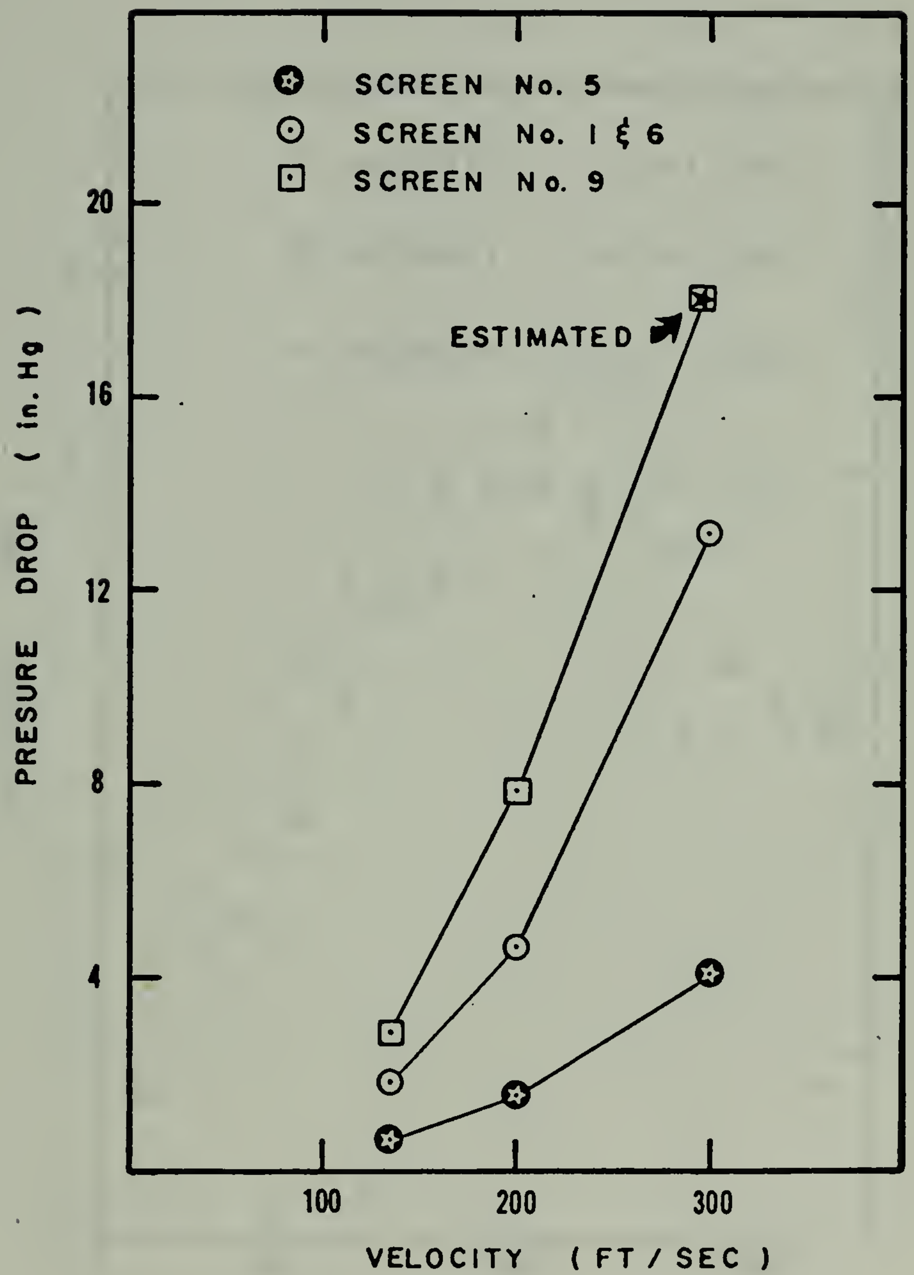


FIGURE 11. PRESSURE DROP ACROSS SCREENS OF INTEREST

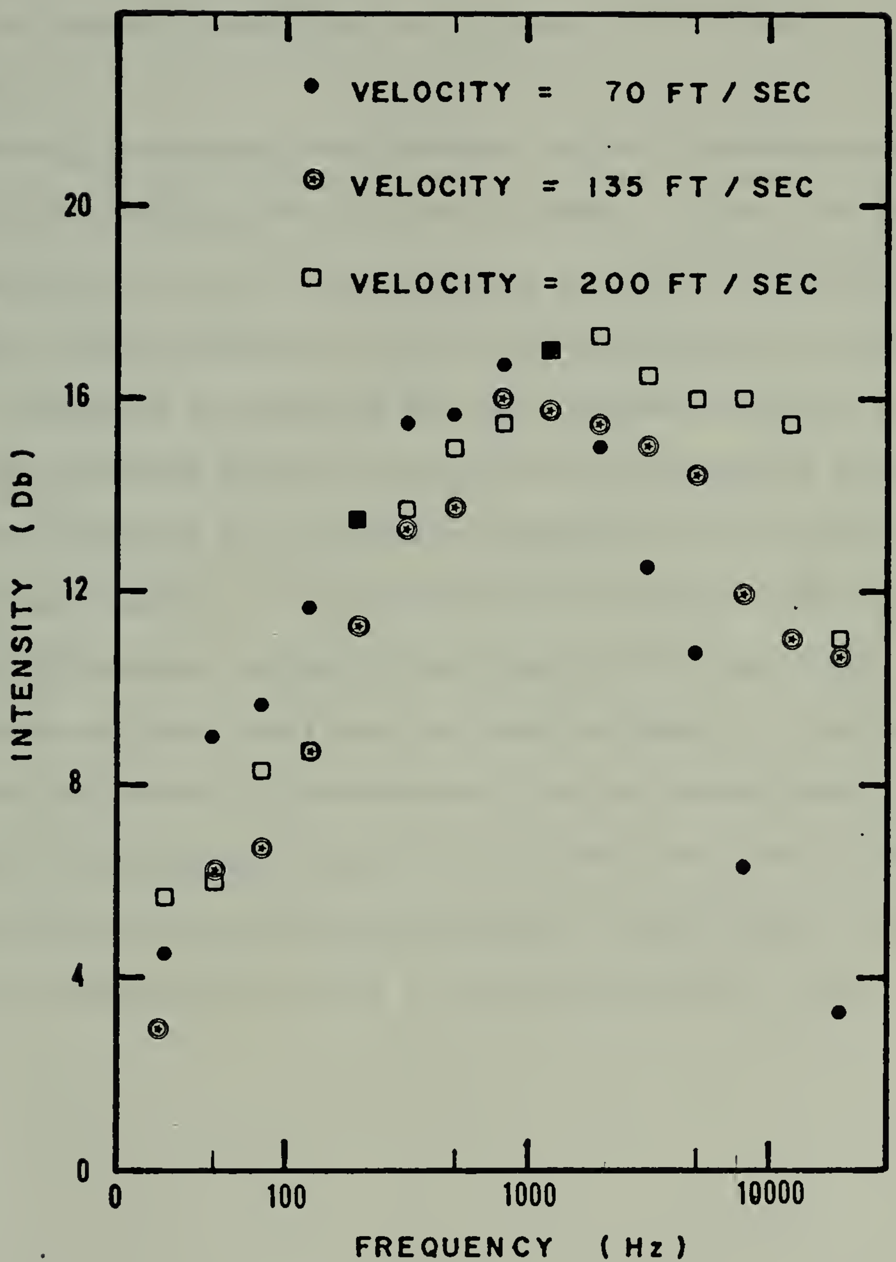
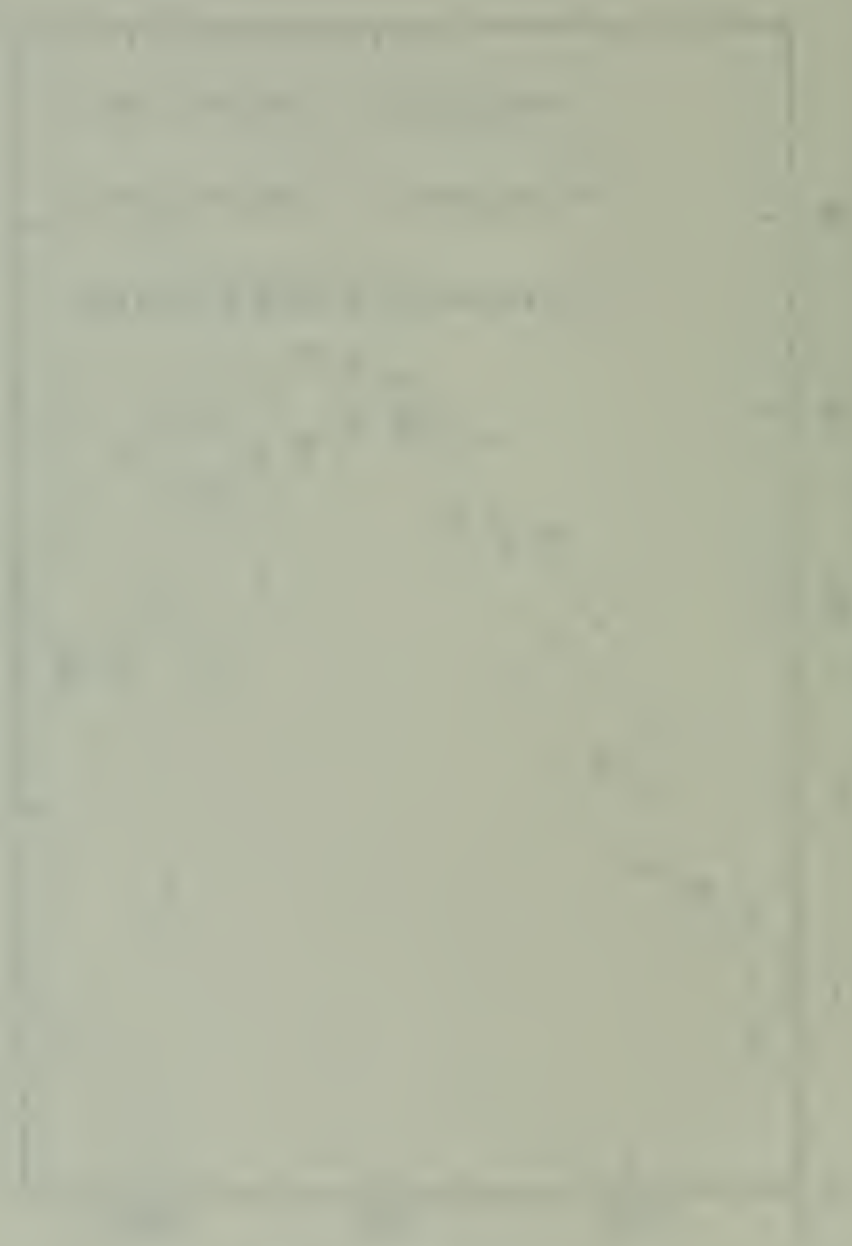


FIGURE 12. VARIATION OF SPECTRAL DISTRIBUTION WITH VELOCITY. DATA TAKEN ON SCREEN No. 1 & 6 BEHIND CTR. PIN.



The results of the electric-discharge experiments were somewhat disappointing. Screen 9, whose spectral distribution looked so promising, produced inferior discharge characteristics, even when compared with the no flow case. Nelson's combination (screens 1&6) still produced the best results and the promise of improving the discharge with turbulence is evident from Figure 13.

Several experiments were performed to try to improve the discharge characteristics resulting from the use of screen 9. First, the combination of screens 6&9 was tested; then, a version of screen 9 with enlarged holes was tested. These modifications did not noticeably alter the discharge performance. Reference 6 postulated that the main effect turbulence has on an electric-discharge region is the creation of homogeneous velocity distribution to compensate for the defects introduced by an electrode element. To investigate whether or not this could be the cause of screen 9's poor discharge performance, further velocity profile data were taken. Only vertical traverses were done, and these are shown in Figure 14. The results do not indicate why screen 9's performance is so poor electrically. If anything, the profile comparisons reinforce the belief that screen 9 should give better discharge characteristics than Nelson's combination. Screen 9 produces a more uniform velocity field in the region behind the pins.

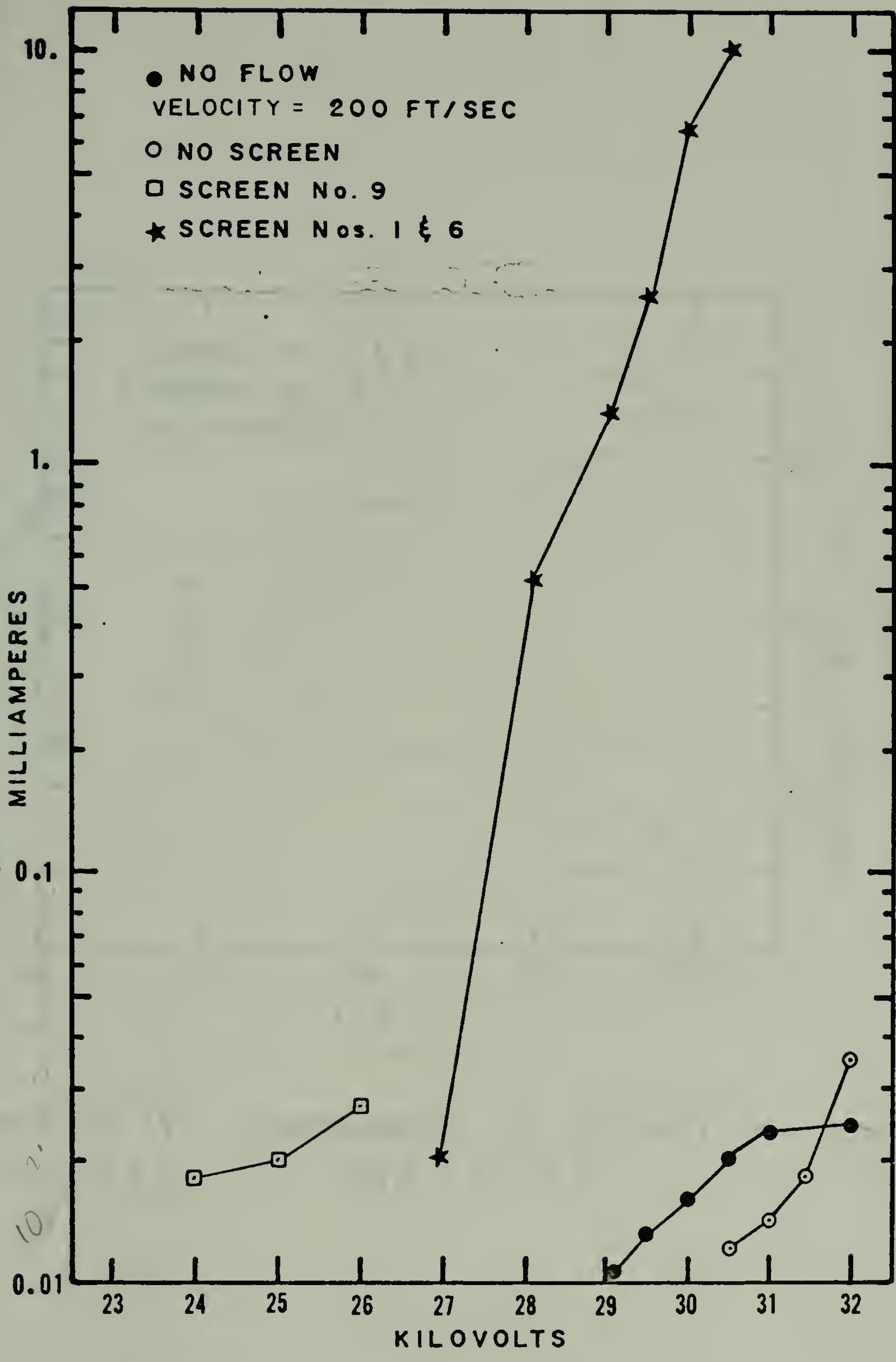


FIGURE 13. ELECTRIC-DISCHARGE PERFORMANCE

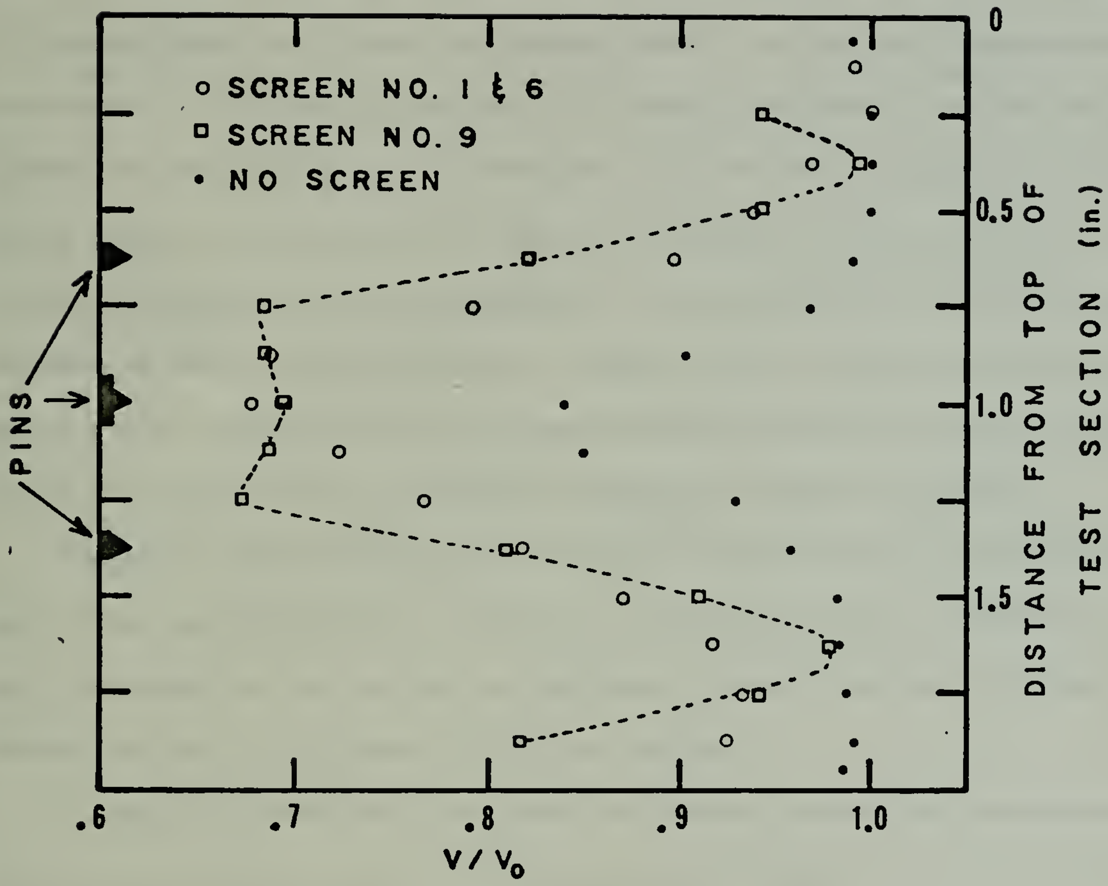


FIGURE 14. COMPARISON OF VELOCITY PROFILES. V_0 = 200 FT/SEC

VI. CONCLUSIONS AND RECOMMENDATIONS

The work of this thesis confirms that a certain kind of turbulence enhances the electric-discharge performance of a gas flowing at near atmospheric pressures. The exact mechanisms involved are not yet fully understood. It appears that two effects are taking place: mixing due to turbulence, and convection. Turbulent mixing has the greater importance, and the desired effect of this mixing can be visualized with the aid of Figure 15. Local space charge that builds up at the pin tips must be dispersed so that growth of this concentration can be delayed. It is believed that this mixing phenomenon is what forestalls arcing. Also, it is believed that high-intensity, small scale turbulence should be less desirable because this type of turbulence has little effect on enhancing gaseous, electric discharges.

The fact that atmospheric air was used as the working medium should not affect the applicability of this work to lasing mixtures. Obtaining an electric discharge in air is just as difficult, perhaps even more difficult than obtaining one in the typical CO_2:N_2:He mixture.

It has been shown that the increased electric-discharge performance obtained with Nelson's screen combination can be applied to discharge regions of larger dimensions. It has also been shown that it makes little, if any, difference what metal materials are used for electrode construction. (Nelson's electrodes were made from aluminum whereas those tested here were made from stainless steel.)

The intensity of turbulence in the discharge region seems to be a function of the flow blockage. As the flow blockage increased, the intensity of the spectral distribution increased. There may be some significance attached

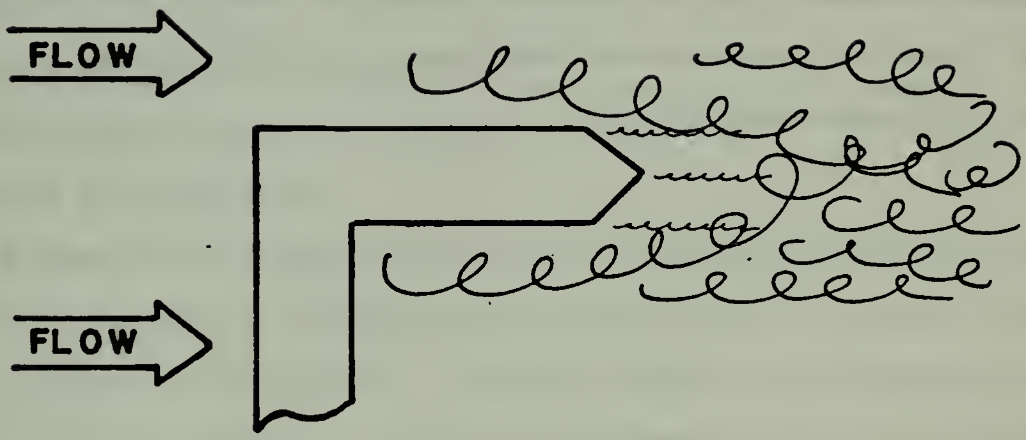


FIGURE 15. DESIRED EFFECT OF SCREEN-GENERATED TURBULENCE ON PIN ELECTRODE.

to the fact that screens 1&6 when used together give a 50% blockage of flow. This may be an optimum for the discharge.

Using plexiglas for the plenum, nozzle, and test section is still a good choice, but a warning about its strength would be appropriate for these applications. If the pressure differences expected exceed 4 psig, it is suggested that 0.5inch or greater thickness be used. Problems encountered with the present power supply were insufficient voltage and power. Consideration should be given to replacing the present power source with one more suitable for laser work.

Because of its superior spectral distribution data and the velocity profiles, it is still felt that screen 9 should prove to be as good or better than Nelson's in performance. A thorough probing of the entire test section is suggested to determine if there are any "dead spots" in the flow field. If a pin falls within a "dead spot," the observed poor electric-discharge performance could be attributed to it. It only takes one pin to experience a low flow region for the discharge to arc and essentially short out the applied voltage. A smoke generator placed in the plenum may be a quick visual aid in determing whether or not any "dead spots" exist. Further research in this area is also needed in order to fully understand the mechanisms involved in electric-discharge stabilization by turbulent flow.

A further conclusion of this work is that a closed-cycle, EDCL system may be constructed at the Naval Postgraduate School with a minimum expenditure of funds. The next step in this project should be the active solicitation of funds from appropriate research activities of the Department of Defense. The amount of monies involved is very small compared to the potential research dividends that could be realized from completing the construction of a closed-cycle, EDCL system. A more suitable power supply has

already been located so that the major holdup of this project is the acquisition of a compressor. (See Appendix)

APPENDIX

CALCULATION OF COMPRESSOR REQUIREMENT

These calculations represent a preliminary analysis to define the compressor requirements of the proposed closed-cycle EDCL system. In order to minimize the leakage of atmospheric gases that would be detrimental to the lasing mixture, it is desired that the lowest pressure internal to the loop be close to atmospheric. High-quality silicone seals should also be used. It is anticipated that the maximum flow rate to be investigated will be on the order of 1500 standard cubic feet per minute (scfm). The compressor chosen must be capable of delivering clean, oil-free gases.

In the case of the nozzle and diffuser, it was assumed that one-dimensional isentropic flow exists. Ideal behavior is also assumed. The ratio of specific heats is 1.54 for the typical CO_2:N_2:He lasing mixture Ref. 8 , but for this analysis 1.4 was used in order to utilize standard tables for air. In the calculations of losses due to friction, it was assumed that the roughness factor of aluminum is the same as for galvanized iron, that is, 0.0005. Atmospheric pressure was assumed to be 14.7 psia.

A. RETURN PIPING

Referring to Figure 16 and working backwards from point 1 to point 13, a "head-loss" calculation was performed. With a flow rate of 1500 cfm, the velocity in this section would be 74 ft/sec. This yields a Reynolds number (Re) of approximately 2.9 x 10^5. Reference 16 gives a means of converting 90^o elbows into terms of pipe length and gives the overall head loss due to friction for pipe flow as

$$h_f = f \frac{L}{d} \frac{v}{2g}$$

where f - friction factor from Moody diagram

L - length of pipe

d - inside diameter of pipe

v - velocity of working medium

This analysis yields h_f = 0.056 psia. Although the accuracy of Fanno flow tables is poor for low Mach numbers, a comparison was made which yielded a h_f = 0.054 psia. Using an equivalent diameter of the diffuser end equal to four times the area divided by the wetted perimeter, the pressure loss for the sudden contraction at point 13 is 0.006 psia Ref. 16 .

B. DIFFUSER

Assuming p_{11} = 14.7 psia and the steady state temperature (T_{11}) is 550°R, an isentropic diffuser analysis gives a pressure loss of 1.64 psia. Using the measured boundary layer thickness found in the test section and the diffuser analysis given in Schlichting Ref. 15 , the diffuser efficiency is 0.89. Using this information the diffuser pressure loss can be calculated to be 1.62 psia.

C. TEST SECTION

The head loss due to friction in the test section was considered to be negligible. The pressure loss across the various screens was determined experimentally by recording this loss with the use of a U-tube manometer. The results can be seen in Figure 11. The pressure drop tends to vary as the square of the velocity.

$$P_{loss} = k_a \frac{v^2}{2g}$$

where k_a is an average proportionality factor determined for each screen or combination of screens:

$k_{1,6} = 0.00381 \quad psia/ft_{air}$

$k_9 \quad = 0.0053 \quad psia/ft_{air}$

$k_5 \quad = 0.00124 \quad psia/ft_{air}$

The measured pressure drops were considerably greater than obtained from the theoretical drag analysis of square mesh grids given in Chapter 3 of Reference 9.

D. NOZZLE

The pressure loss in the nozzle depends upon the desired exit conditions. The existing area ratio (A_8/A_9) is 10.13. Using the maximum condition expected, M = 0.40, an isentropic analysis yields a nozzle pressure loss of 1.7 psia Ref. 10 .

E. PLENUM

Friction losses in the plenum are considered to be negligible. The experimental analysis of the pressure drop across screen 5 indicates that $P_{loss} \doteq 0.03$ psia for the maximum flow rate expected. The loss for the sudden expansion at point 5 can be approximated by

$$h = \frac{v_6^2}{2g} \left(1 - \frac{A_6}{A_5} \right)^2$$

Under maximum flow conditions this analysis yields $h_1 = 0.013$ psia Ref. 17 .

F. OUTLET PIPING

An analysis was done, as for the return piping, which yielded $h_f = 0.055$ psia.

G. HEAT EXCHANGER

That the heat exchanger can be designed with a pressure loss of 2.0 psia or less is considered a reasonable assumption.

H. SUMMARY

Figure 17 compares the characteristics of the proposed closed-cycle system with the performance of a suitable compressor that is available from the Gardner-Denver Company Ref. 7 .

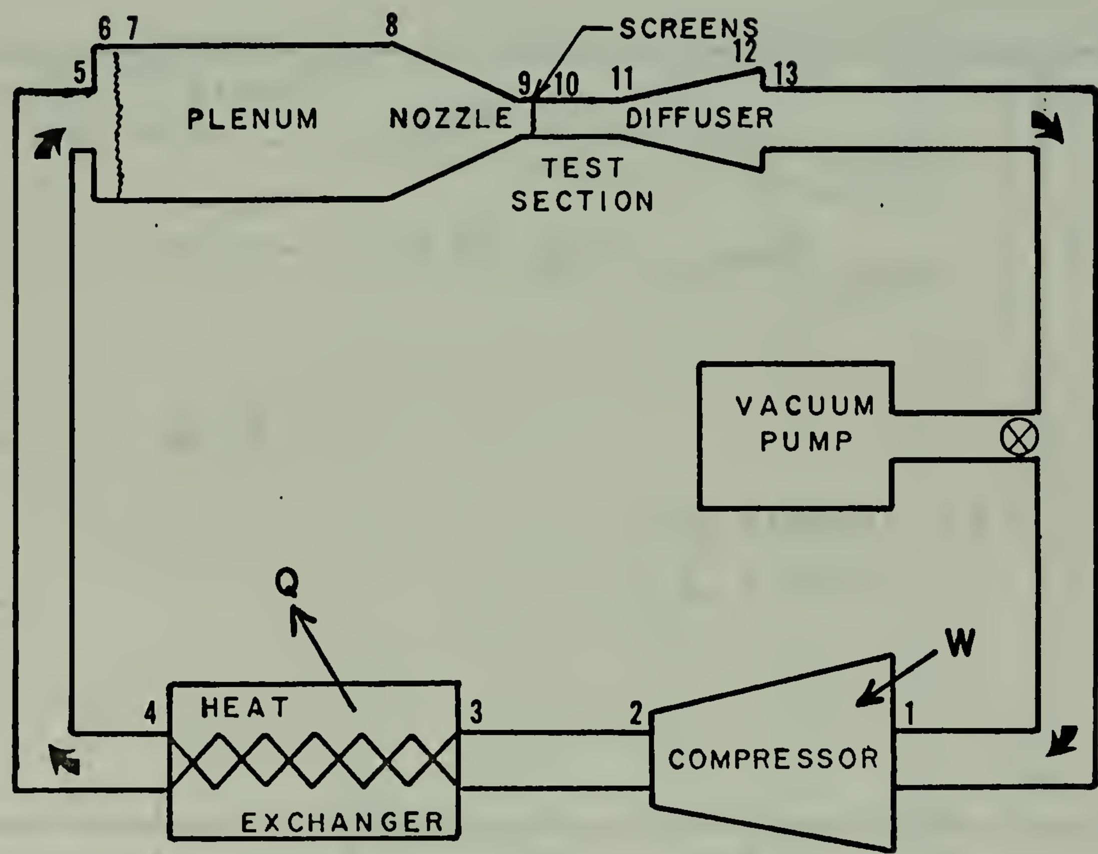


FIGURE 16. SCHEMATIC OF CLOSED-CYCLE SYSTEM FOR COMPRESSOR REQUIREMENT CALCULATIONS.

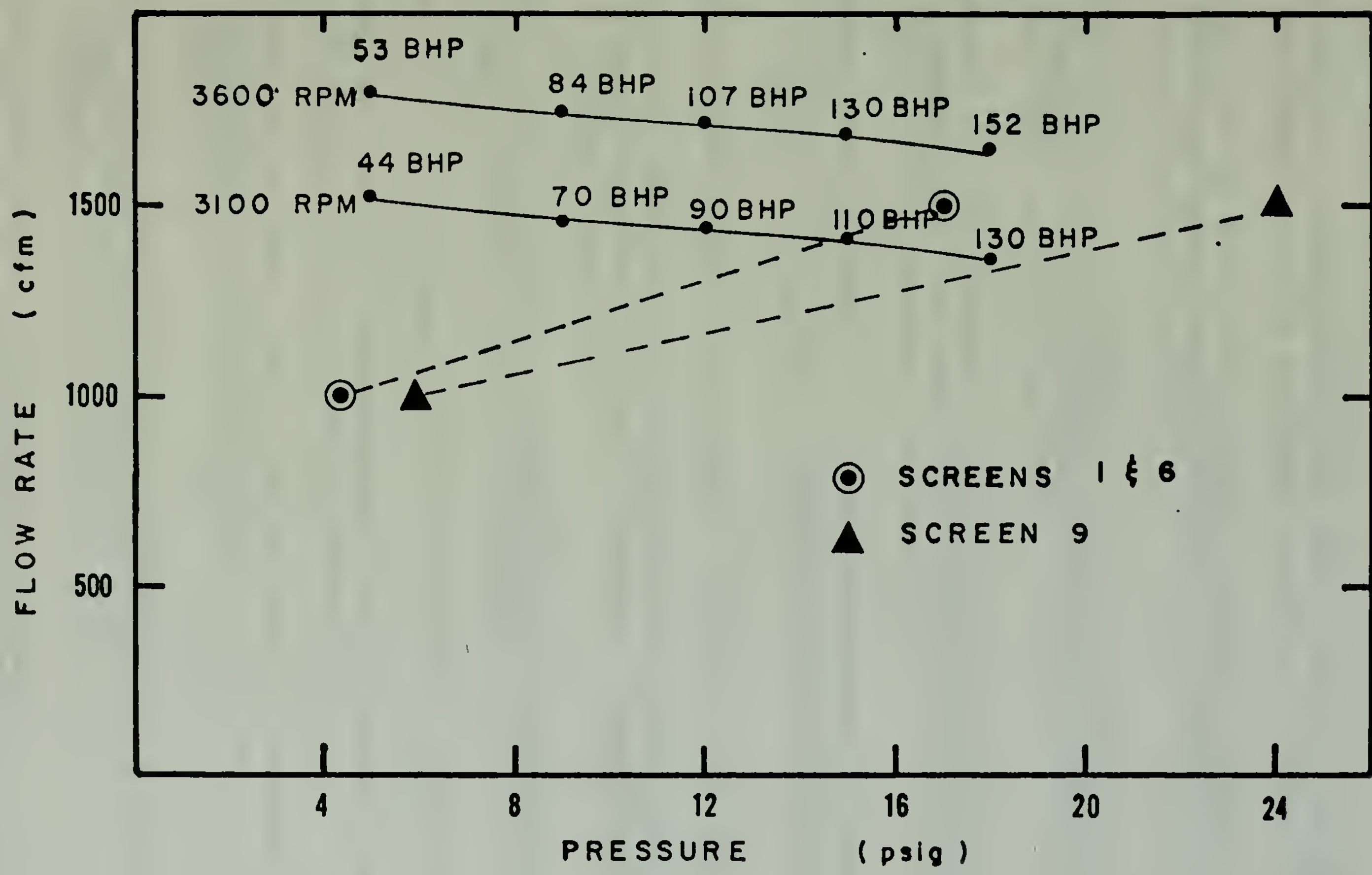


FIGURE 17. COMPRESSOR REQUIREMENT.

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This thesis is primarily concerned with the application of controlled turbulence to electric discharge convection lasers (EDCLs). A preliminary design of a closed-cycle, EDCL system has been accomplished. Experimental investigations into the mechnisms of turbulent flow and its stabilization of gaseous, electric discharges were made. Spectral distribution, velocity profile, and power consumption data taken in a discharge region are presented. Turbulence was generated by various screens or combination of screens in an attempt to further

understand the phenomena involved.

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for electric discharge
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